

# DEVELOPMENT OF A TELEOPERATED VEHICLE

*by*

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# DEVELOPMENT OF A TELEOPERATED VEHICLE

*A Thesis Submitted*

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for the Degree of  
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*by*

BHAGIRATHSINH N GOHIL

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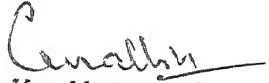
My Parents and all the people  
in manufacturing Science Lab.

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CERTIFICATE

This is to certify that the thesis entitled,  
"DEVELOPMENT OF A TELEOPERATED VEHICLE" by  
Mr. Bhagirathsinh N. Gohil has been carried out under  
our supervision and has not been submitted elsewhere  
for a degree.

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## NOMENCLATURE

$\omega_1$	=	Angular velocity of driving motor
$\omega_2$	=	Angular velocity of steering motor
$r$	=	Wheel radius
$R$	=	Radius of circular path of wheel centres
$R_p$	=	Radius of circular path of the vehicle
$V_p$	=	Linear velocity of the vehicle
$C$	=	Centre to centre distance between the motor shaft and the driving shaft
$d_1$	=	Pitch cone diameter of the gear
$d_2$	=	Pitch cone diameter of the pinion
$m$	=	Module of the gear
$\delta_1$	=	Pitch cone angle of gear
$\delta_2$	=	Pitch cone angle of pinion
$R_1$	=	Conc distance.

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## ABSTRACT

The objective of the present work is to design and fabricate a teleoperated vehicle which can act as the base of a mobile Robot. Accordingly, a three wheeled vehicle is designed and constructed. All the wheels are driven and steered simultaneously. Separate motors and controls are provided for driving and steering. The control system can be operated either manually or through a programmed micro-processor. The vehicle is designed to take any radius of path-curvature. The fabricated vehicle is demonstrated to move along various prescribed paths through programmed control.

## CHAPTER 1

### INTRODUCTION

#### 1.1 Introduction

The use of the robots in various sectors is increasing day by day as they can replace humanbeings in hazardous and monotonous jobs, as well as, higher precision, accuracy, repeatability and speed can be achieved.

At present most of the robots in use are of stationary type, i.e. their base remain fixed to the ground. Such robots are capable of working within a fixed work space which depends on the size and configuration of the robots. Such robots can work satisfactorily so long as the situation does not demand continuous change in the position of working. However, there are certain areas of application where the work-space of the robot is not known in advance, in such cases it is imperative that robot changes its position in order to perform the job. The application of robots in nuclear establishments, underwater, deep mines etc. often demands that the robot moves bodily to cover a much wider workspace. Such robots where the base of the robot moves are called mobile robots [1,2] .

#### 1.2 Mobile Robots and Teleoperated Vehicles

Mobility or locomotion required in a mobile robot can be achieved in two ways namely legged locomotion and wheeled

locomotion [3]. Design and construction of legged locomotion which are essential for uneven terrain are quite involved and expensive [4,9] . For applications on even terrain, like factory floors, wheeled locomotion, which is simpler, is sufficient. In wheeled locomotion, as the name suggests, wheels are used to achieve the desired motion of the robot, when wheeled locomotion is used and when the robot has to change level, at that time slope can be provided instead of staircase [5].

For wheeled robots the motion of the robot can be controlled in three possible ways. For a decided path one possible method is to use underground wires or floor paints along the given path. Corresponding sensors are mounted on the robot which pick up signals and guide the robot along that path [6,7] . This method involves more hardware and so is not very flexible as it required change of network of wires or repainting the floor for changing the path. The second method consists of writing a program to control the motion of the wheels in order that the robot moves along a certain path and reaches the destination. Both open loop and closed loop control systems can be used depending on the situation. Here processors get the signals from the program and actuate the actuators accordingly so that the desired path is executed. In this mode, with the help of sensors, obstacles can be sensed and avoided, by altering the path of vehicle, through an appropriate algorithm [8].

In this approach, for generating a new path no change in the hardware is necessary, the only requirement is to write a new program. The third way to control the motion of a robot is by teleoperation. In this mode a human operator controls the motion of the robot from a distance. The operator can view the robot either directly or on a screen and can guide the robot to the destination by avoiding obstacle, if any, on the way. In this case no additional hardware or software is required for changing the path as the operator is controlling the motion directly through the interface.

### 1.3 Objective and Scope of the Present Work

The objective of the present work is to develop a vehicle which can act as the platform of a mobile robot. The motion of this platform is to be controlled in two ways namely, manual teleoperation and programmed modes. A controller using digital circuit is developed for manual operation mode and an 8085 microprocessor kit is used for programming the motion. For taking various paths it is often required to divide the total length into a number of segments. Accuracy of tracking various segments is better with smaller radius of turning. In the present model the minimum radius of curvature is kept at zero. The entire operation is carried out in an open loop control scheme.

The scope of the work is limited to simple paths only. No sensors for sensing the obstacles are mounted and so there can not be any dynamic generation of path. The vehicle is not controlled by the radio signals and so the zone is limited by the length and the entangling of the wires. The model is demonstrated for 3 different paths in the programmed mode.

## CHAPTER 2

### KINEMATICS, MECHANICAL DESIGN AND FABRICATION

#### 2.1 Introduction

The proposed design is for a three-wheeled vehicle with wheels placed symmetrically at  $120^\circ$  on a circle. All the three wheels are driven simultaneously by a motor placed at the centre of the platform to give uniform drive. While turning all the wheels are steered simultaneously by a second motor. Because of simultaneous steering the minimum radius of turning is zero.

In the present chapter first the kinematics of the vehicle is described. This explains how the change in the path of the vehicle results when either or both of the driving and the steering motors rotate. This is followed by the details of mechanical design of the vehicle. Some typical arrangements of the components which are important at the fabrication stage are also noted.

#### 2.2 Kinematics of a Three Wheeled Vehicle

As already mentioned, the three wheels of the vehicle are placed on a circle at  $120^\circ$  with each other. Figure 2.1 shows one such wheel and also explains how it is connected to the driving motor. The other two wheels are connected to the same motor in identical fashion. Thus, all the three wheels get the same driving (either forward or reverse)



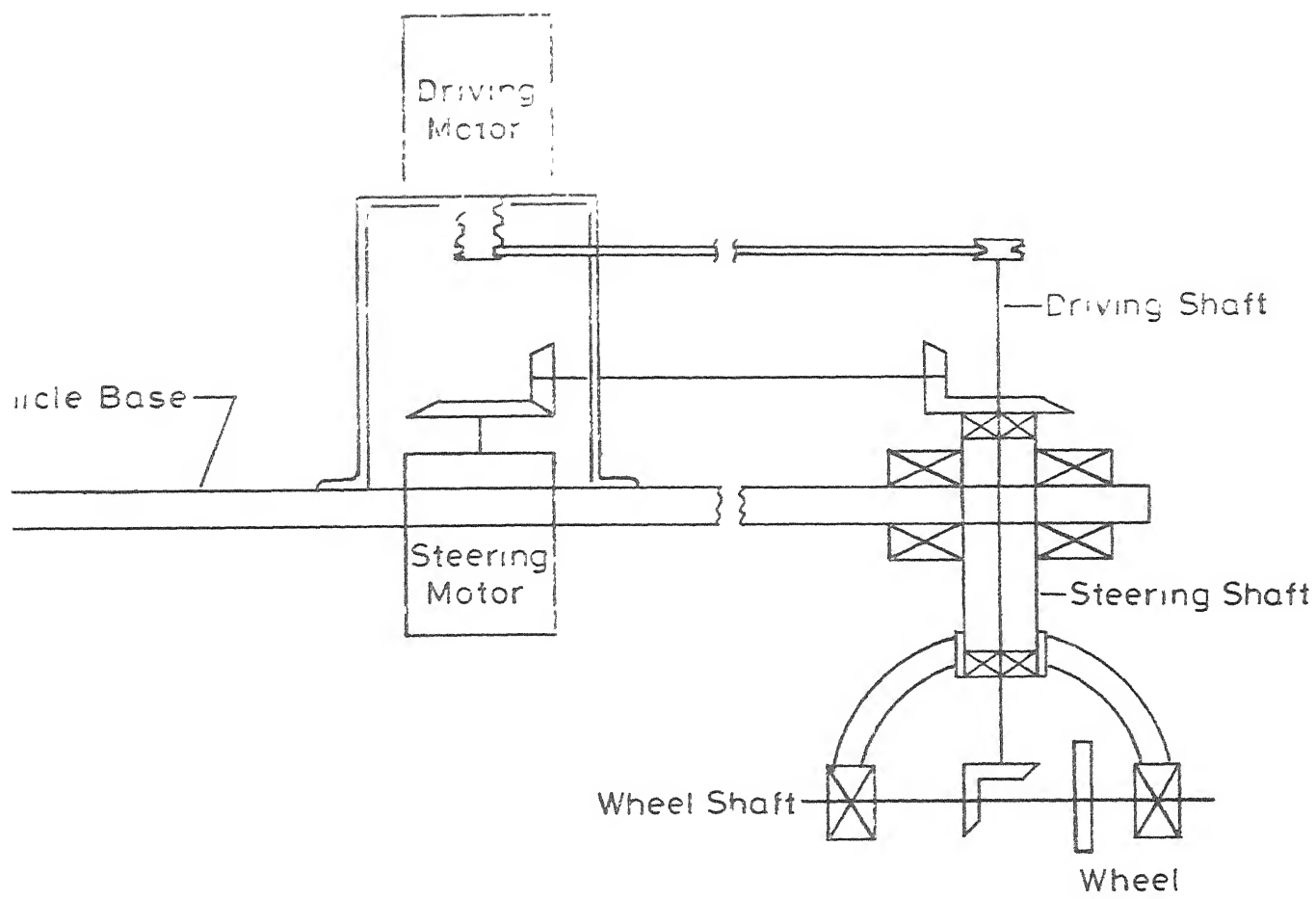


Fig.2.1 Schematic diagram of the vehicle.

motion simultaneously. The steering motor is also shown in the same figure. It should be noted that the steering shaft acts as the housing for both the driving and the wheel shafts. Again the same steering motor is connected to all the three wheels in an identical fashion.

The driving shafts are connected to the driving motor by a direct belt-pulley drive with unity angular velocity ratio. The wheel shafts are connected to the driving shafts again with unity angular velocity ratio through bevel gearing. Hence if the angular velocity of the driving motor is  $\omega_1$ , the linear velocity of the centre of the wheels and that of the platform is given by  $\omega_1 r$  where  $r$  is the radius of the wheels.

As indicated in Figure 2.1, the wheels are offset from the driving shaft axis by a distance  $r$  equal to the wheel radius [5]. With this eccentricity, it is obvious that if only the steering motor is given one rotation while the driving motor is kept stationary then all the wheels come back to their original position without any movement of the platform. Of course each wheel rolls one full circle around its corresponding driving shaft axis and at the same time completes one revolution about its own axis. Thus the wheels come back to their original location and the orientation.

For any arbitrary amount of rotation of the steering motor with the driving motor stationary, all the wheels change

their position and orientation in identical manner while the vehicle base neither changes its position nor its orientation.

Let us now consider the movement of the vehicle when both the driving and the steering motors are rotated simultaneously at different speeds. For this we consider only one of the wheels as all the wheels have identical motion.

Let the angular velocity of the driving motor be  $\omega_1$  and that of the steering motor be  $\omega_2$ . Then the velocity of the centre of the wheel due to the driving motor is  $\omega_1 r$  while that due to the steering motor is  $\omega_2 r$ . As both these velocities at any instant are in the same direction, the magnitude of the resultant linear velocity of the wheel centre is  $(\omega_1 + \omega_2)r$ . The direction of this velocity is given by the direction of the vector  $\vec{\omega}_2 \times \vec{r}$  where vector  $\vec{r}$  represents the eccentricity of the wheel. For constant value of  $\omega_2$  the path traversed by all the wheel centres will be circles of radius  $R$ (say), when

$$\omega_2 R = (\omega_1 + \omega_2)r$$

or

$$R = \frac{\omega_1}{\omega_2} r + r$$

As explained in Figures 2.2(a) and 2.2(b), for circular paths of the wheel centres of radius  $R$ , the vehicle base moves

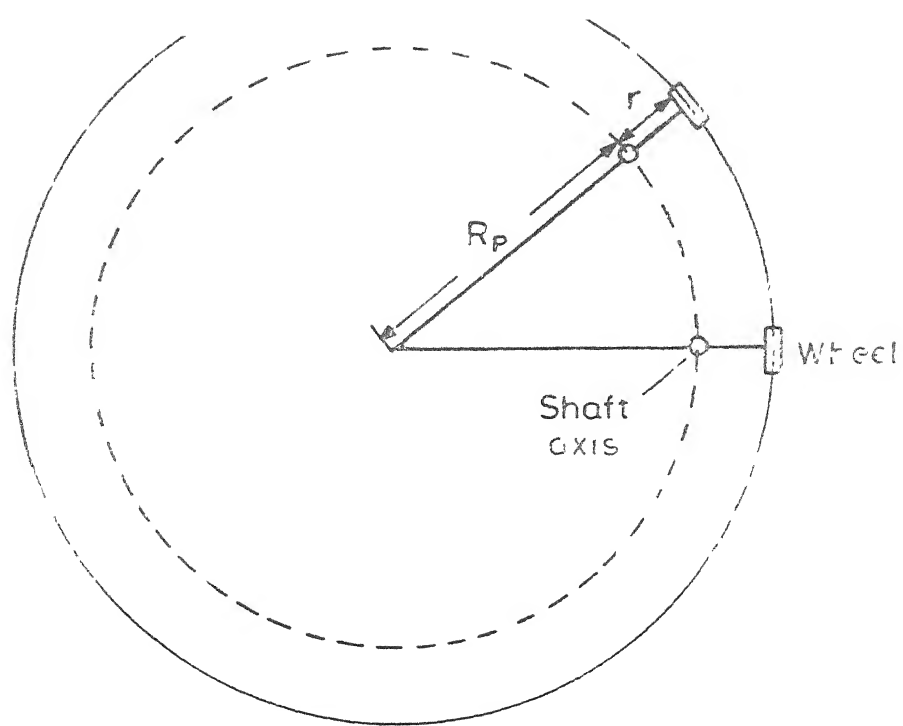


Fig 2 2(a)

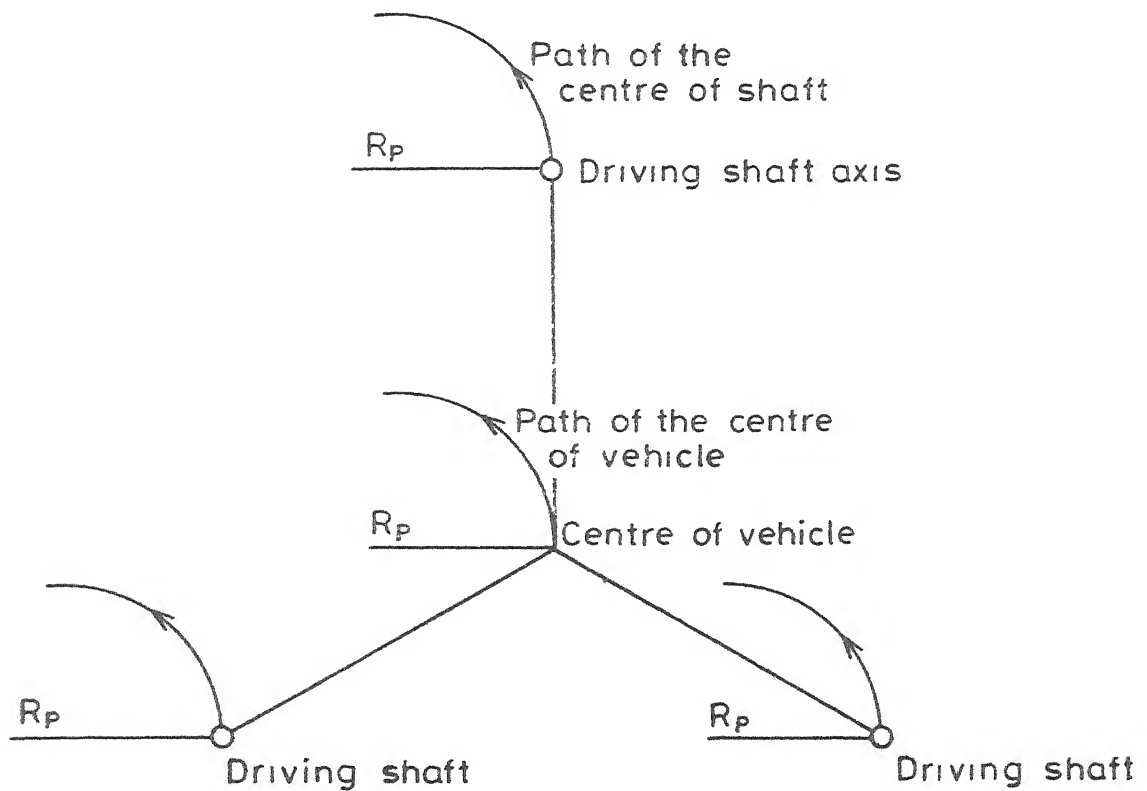


Fig. 2.2(b) Path of the vehicle when both the motors rotate.

in a circle of radius

$$R-r = \frac{\omega_1}{\omega_2} r .$$

So finally the linear velocity of the platform is obtained as

$$V_P = (\omega_1 + \omega_2)r \quad (2.1)$$

along a circle of radius

$$R_P = \frac{\omega_1}{\omega_2} r . \quad (2.2)$$

By choosing different values of  $\omega_1$  and  $\omega_2$  the platform can be moved at different velocities along circles of varying radii. It is obvious that with the steering motor stationary i.e.  $\omega_2 = 0$ , the platform moves along a straight line ( $R \rightarrow \infty$ ). In either case the orientation of the vehicle remains unchanged.

### 2.3 Mechanical Design of the Vehicle

To determine the torque required to drive and steer the vehicle, all the calculations are carried out by assuming the mass of the vehicle to be 30 Kg. Few simplifications are made by considering the worst case and so the actual torque requirement is less than that determined from this calculation. In order to determine the torque, traction required to drive the vehicle is to be found. Traction in turn depends on the

condition of surface on which the vehicle is supposed to be driven. Empirical data are available in the hand book which are used for car driving. These data are assumed for the present case.

Data given in the hand book [ 10 ] .

<u>Kind of Surface</u>	<u>Traction in lb/1000lb</u>	<u>Traction in N/kg</u>
(1) Hard smooth asphalt	11	.10791
(2) Wood paving	13	.12753
(3) Good macadem	17	.16677
(4) Bad macadem	22-45	.216-.44
(5) Cobbles	26	.255
(6) Bad cobbles	upto 110	upto 1.0791.

From the above data the condition of good macadem is used for the present case. The actual surface will be better and hence the torque required will be less than that computed.

For present case the total traction required

$$= 0.16677 \times 30 = 5.0 \text{ Nt.}$$

So total torque required for driving

$$= \text{traction} \times r$$

$$= 5 \times \frac{3.25}{100} = 0.1626 \text{ Nt-m.}$$

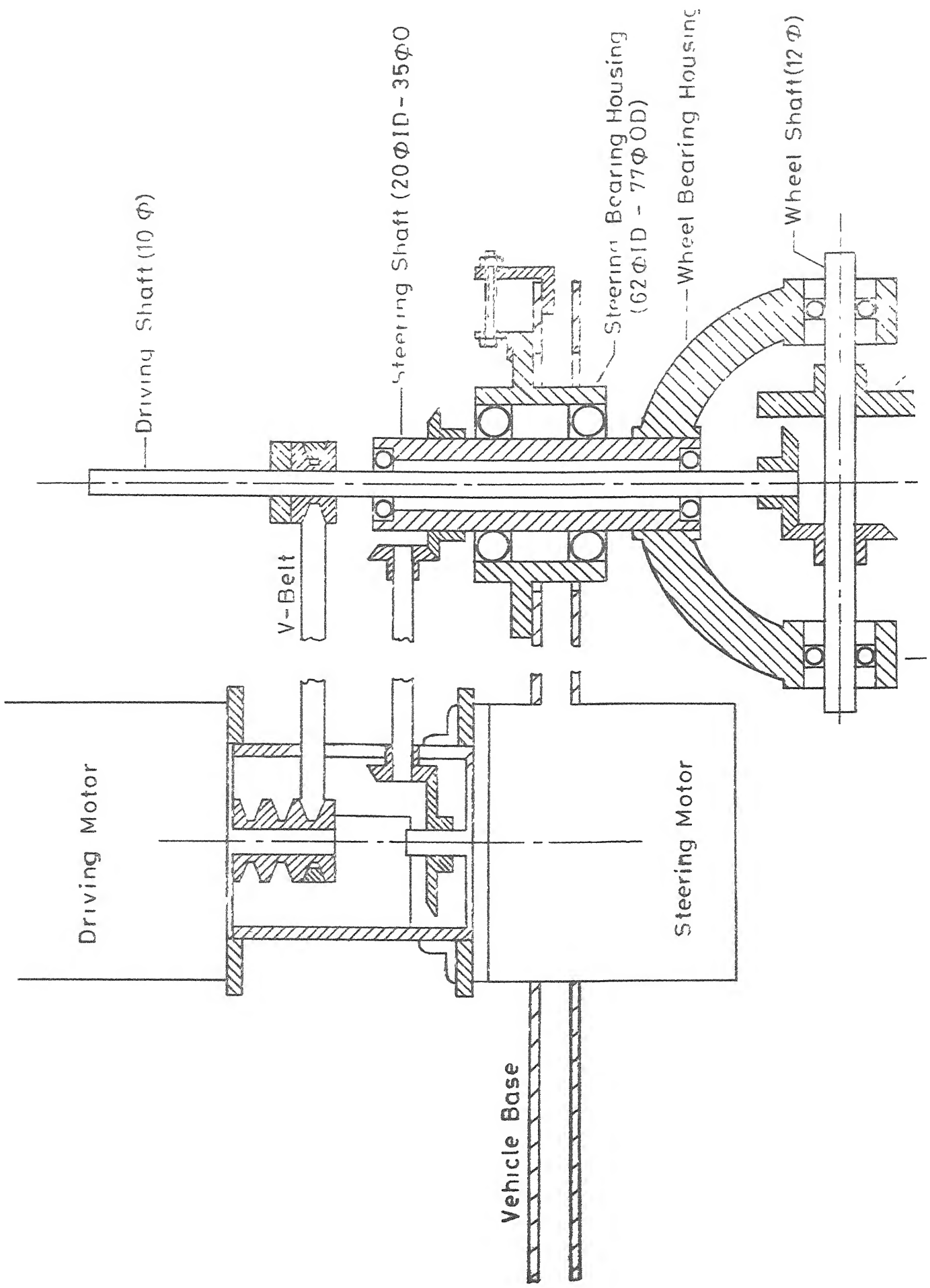
The torque required for steering is equal to that for driving, as in both cases the wheels are rolling.

In addition to this there will be inertia torque acting which is very difficult to determine. However, depending on the desired acceleration this inertia torque can be much more than the torque required for traction. Moreover, friction torques at various places like belts, bearings etc. also add to the requirement. From the list of stepper motors available, motor with 1.96 Nt-m torque rating is chosen to suffice for any future addition on the vehicle.

#### Details of Components:

Each wheel assembly has three shafts namely, the wheel shaft, the driving shaft and the steering shaft enclosing the driving shaft (Figure 2.3). The driving shaft is taken of 10 mm diameter and corresponding bearing available is of size 10 mm-26 mm internal-external diameter [11]. The steering shaft encloses the driving shaft and will support it at ends with bearings. This shaft is supported on the vehicle base with two bearings and so according to the bearing size the outer diameter of the steering shaft is kept at 35 mm. The wheel shaft is kept of 12 mm diameter and is supported at bearing housing by corresponding bearings for the shaft size.

From the driving motor to the driving shaft the motion is transferred by using V belt of 450 mm length and 9 mm





thickness. Pulleys used are of 30 mm diameter at both motor end and driving shaft and to keep the velocity ratio as unity. From the driving shaft, the motion is transferred to the wheel shaft through a pair of bevel gears. Gears are made of aluminium. The velocity ratio is kept one and gear PCD is taken as 46 mm and module 2 mm.

Initially it was decided to use V belts for transmitting motion from the steering motor to the steering shaft. However, belts were not transmitting the motion effectively and so it was decided to use bevel gears for transmitting this motion as well. Two sets of gears are used to transmit the motion with overall velocity ratio unity [12]. From the steering shaft, the motion is directly conveyed to the bearing housing. The bearing housing is of circular shape (Figure 2.5) and the wheel and the bevel gears are enclosed in the space between supporting bearings in the housing.

Calculations are presented in Appendix 1 for detailed design of gears and belts.

## 2.4 Mechanical Fabrication

The vehicle base is made of Aluminium sheets. Two 50 cm x 50 cm aluminium sheets of  $\frac{1}{8}$ " ( $\approx 3.2$  mm) thickness are used for this purpose. Both the sheets are separated by 12.5 mm thick spacers. The spacers give additional strength to the base and use of the sheets makes cutting of slots in the

base easier.

The steering motor is mounted at the centre of the base. Bearing housings supporting steering shafts are mounted  $120^\circ$  apart. Oval shaped slots are cut for adjusting tension of the belts. The entire assembly of steering bearing housing to the wheel is made adjustable so as to slide inward or outward. Bolt and nut are used for this adjustment which in turn adjust the tension in the belt. Once the tension is adjusted then the steering bearing housing is tightened with the base by four, sets of nuts and bolts (Figures 2.4(a) and 2.4(b)).

The bearing housings of wheel bearings are made of Aluminium castings and holes for the wheel shaft bearings and steering shafts are bored at  $90^\circ$  with each other (Figure 2.5).

The driving motor is also placed at the centre of the base and on the top of the steering motor (Figure 2.6). Care is taken to align the shafts of the steering and the driving motors. The driving motor is supported on the steering motor by means of a hollow cylindrical piece having flat surfaces on either sides to fix with both the motors as well as the vehicle base. Three slots at  $120^\circ$ , are cut in the cylindrical piece to let the belts and shafts of the gears pass through them. This cylindrical piece together with the steering motor is connected to the base by

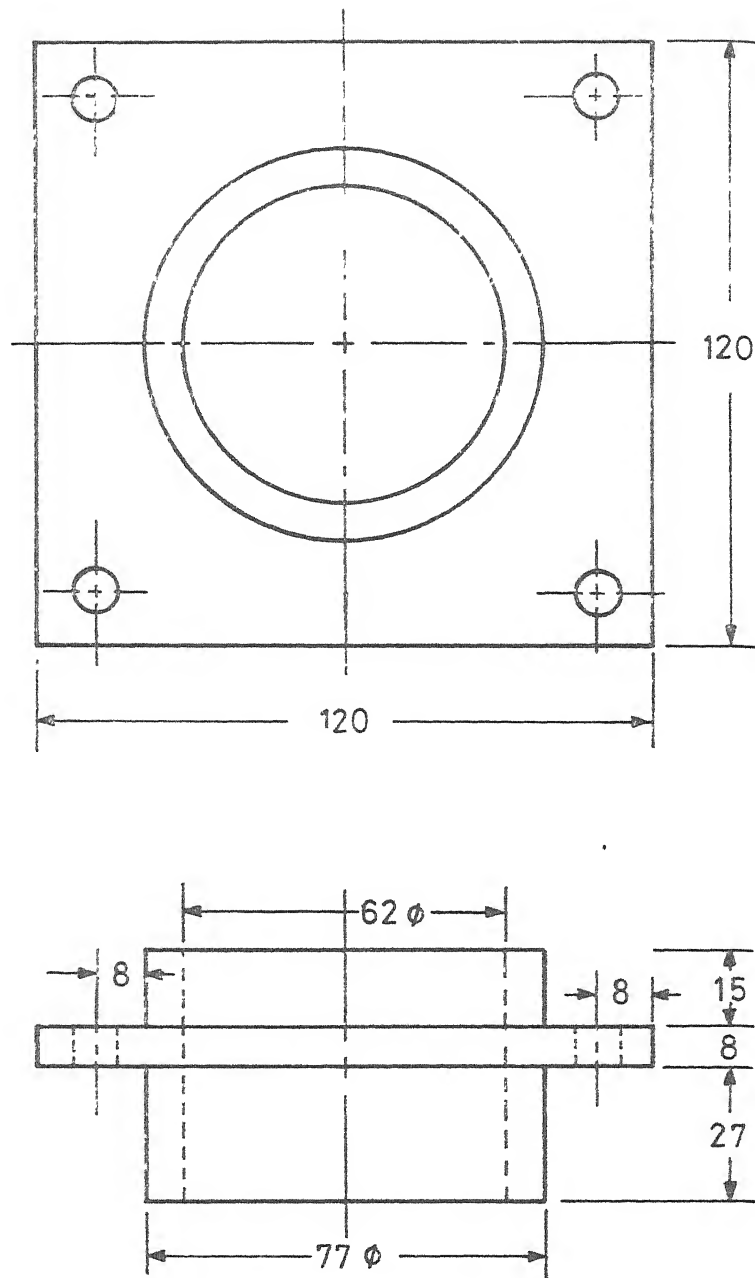


Fig.2.4(a) Bearing housing for steering shaft

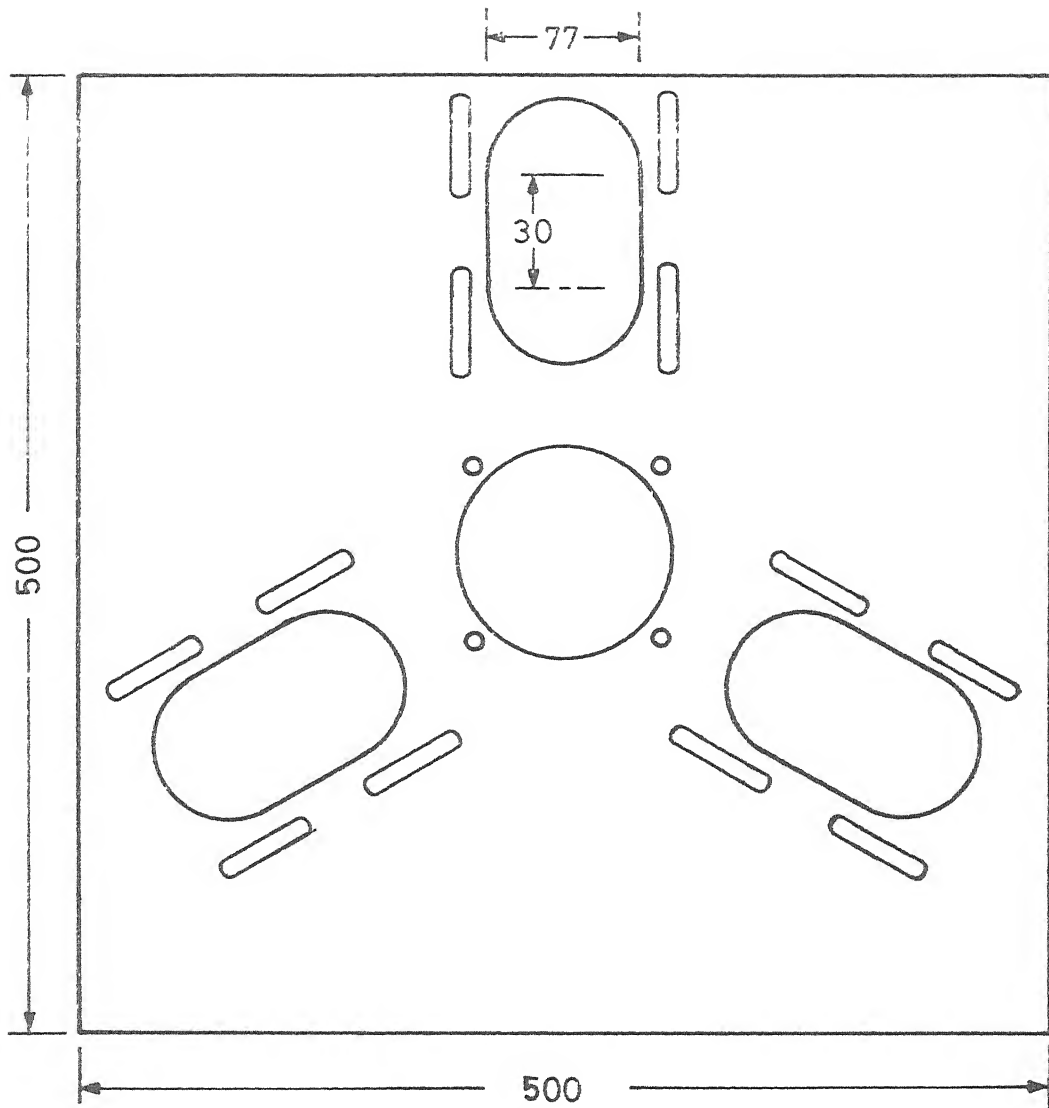


Fig. 2.4(b) Vehicle base.

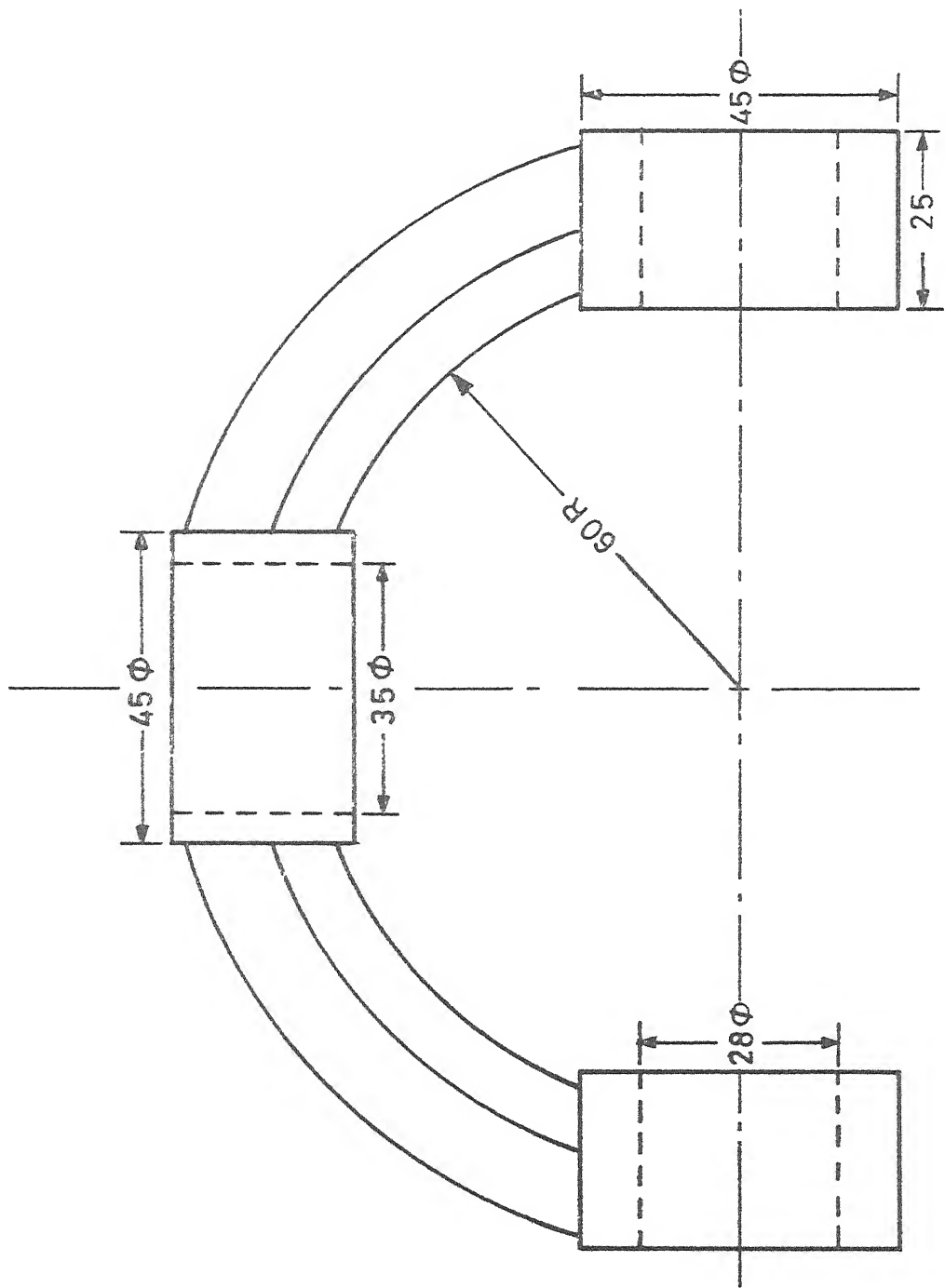


Fig. 2.5 Bearing housing of wheel shaft.

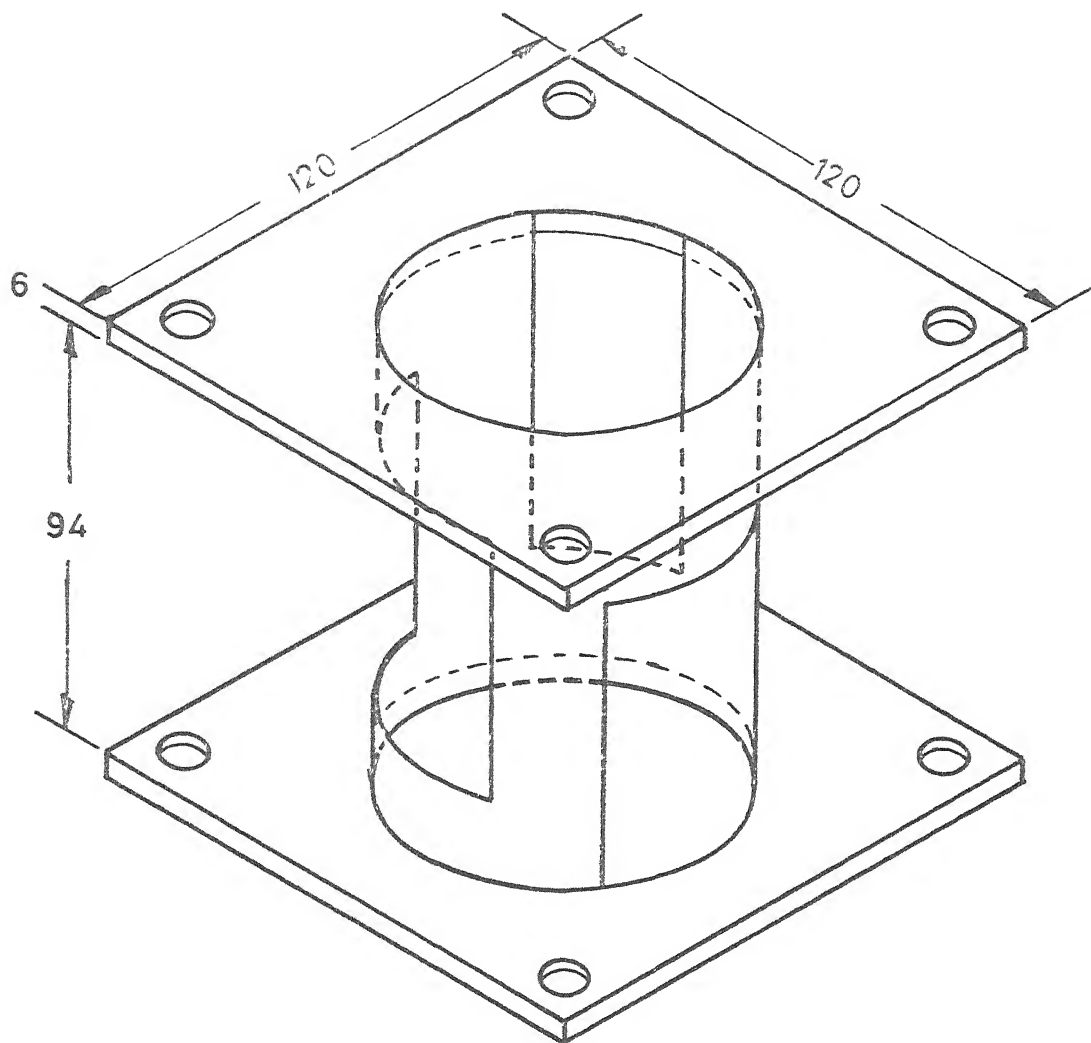


Fig. 2.6 Spacer between two motors

four bolts and is connected with the driving motor by four screws.

## CHAPTER 3

## DRIVE AND CONTROL CIRCUITS FOR VEHICLE MOTION

## 3.1 Introduction

In the vehicle stepper motors are used for giving both the driving and the steering motions. By controlling the speed and number of rotations of each motor, the effective motion of the vehicle can be easily controlled. As already mentioned, the vehicle motion is controlled in two modes, namely, manual and programmed modes. The present chapter describes the principle and method adopted for above modes and various circuits used to achieve this purpose. An algorithm for controlling the motion of both the motors simultaneously using a microprocessor is also included.

A stepper motor is an electromagnetic incremental actuator which converts digital pulse inputs to analog output shaft motion. The shaft of the motor rotates by  $1.8^\circ/\text{pulse}$  and thus has 200 steps/revolution. It has four windings which have to be energised, in correct sequence, in pairs. By reversing the sequence the motor rotates in the opposite direction. Following table gives the sequence for both rotations. The same sequence is repeated after every four steps [13,14,15] .



TABLE 3.1

Step No.	State of Phase				State of phase for reverse direction			
	I	II	III	IV	I	II	III	IV
1	1	0	0	1	1	0	0	1
2	1	0	1	0	0	1	0	1
3	0	1	1	0	0	1	1	0
4	0	1	0	1	1	0	1	0

### 3.2 Design of Control Circuit and Power Supply

In the present work initially stepper motors of 0.687 Nt-m torque capacity and rating of 12V and .67 amp/phase were used. However, the torque supplied was found to be inadequate. So stepper motors of 1.96 Nt-m torque capacity and rating of 12V and 1.25 amp/phase are used.

#### Power Supply:

Two 12V supplies for two motors and one 5V supply for the control circuit are used. All three supplies are housed in a single unit. Figure 3.1 shows the circuits used for these supplies. The 5V supply is also made variable for giving different voltages in the range 2-12 V. To get uniform voltage level the regulators 7805 and 7812 are used for 5V and 12V supplies respectively. Since each motor requires high current, power transistors 3055 are used in 12V supplies. For 12V supplies capacitors of high values are used

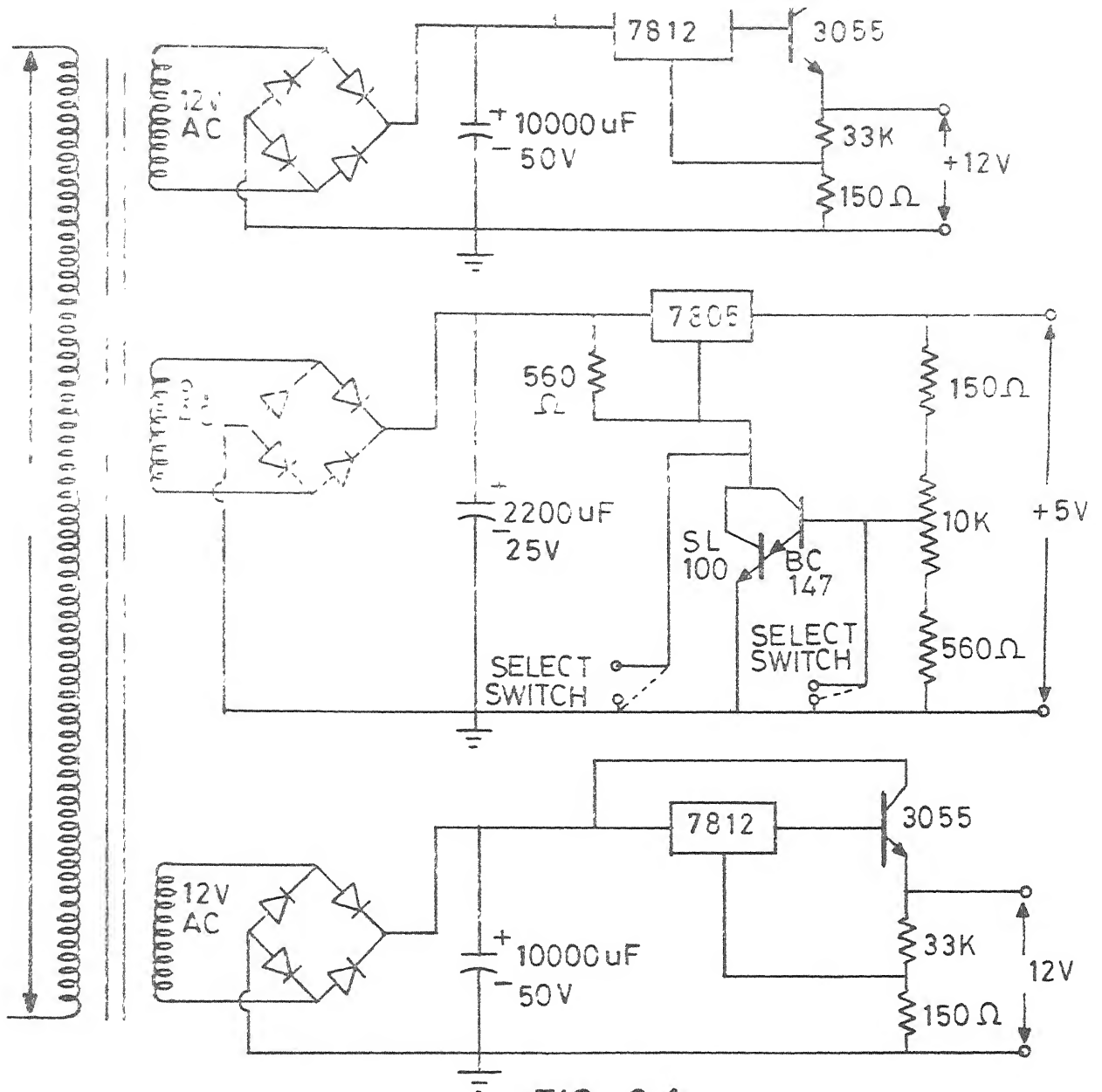


FIG. 3.1  
Ckt diagram for power supply

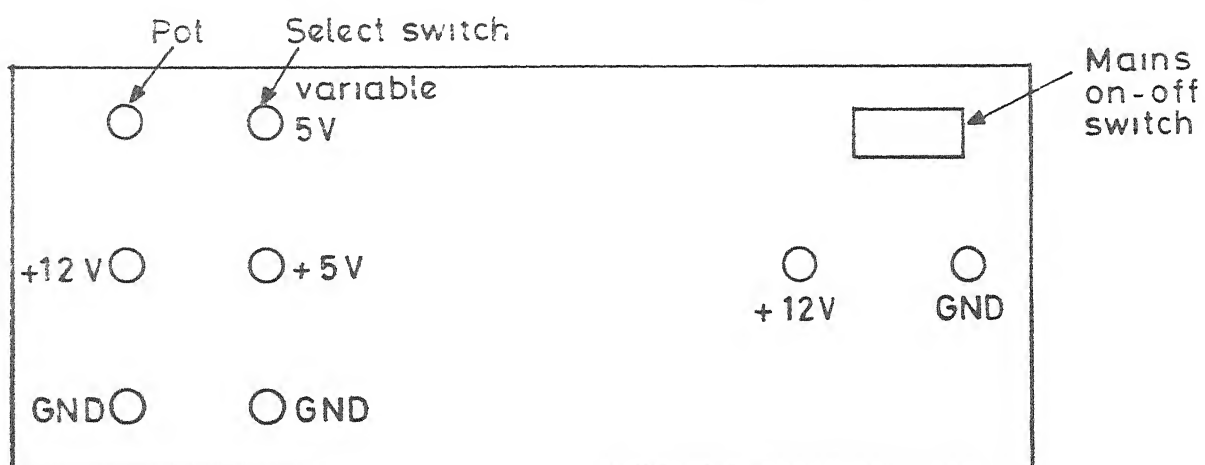


FIG. 3.2

to minimize the ripple. Figure 3.2 shows the front view of power supply giving details of layout of output sockets.

### Control Circuit

Figure 3.3 is a block diagram of the control system used to control the motion of each stepper motor and hence of the vehicle. As seen from Figure 3.3, the control system has four distinct parts. First two parts, namely the manual controller and the microprocessor are supplying identical signals to the translator and the select switch position decides the input to the translator. The translator takes in these signals and gives four pulses in correct sequence to the stepper motor drive circuit which in turn provides the pulses in correct sequence to the motor. First let us explain the manual controller along with the translator. Thereafter, we take up the microprocessor part followed by the drive circuit.

### Manual Controller and Translator

Two identical circuits for two motors are used and so only one is explained here. The speed of the stepper motor depends on the step rate or pulse frequency<sup>given</sup> by the manual controller while the direction is controlled by the direction signal given by the controller.

For generating clock pulses, hex schmitter is used [16]. This schmitter when connected with capacitor and resistance

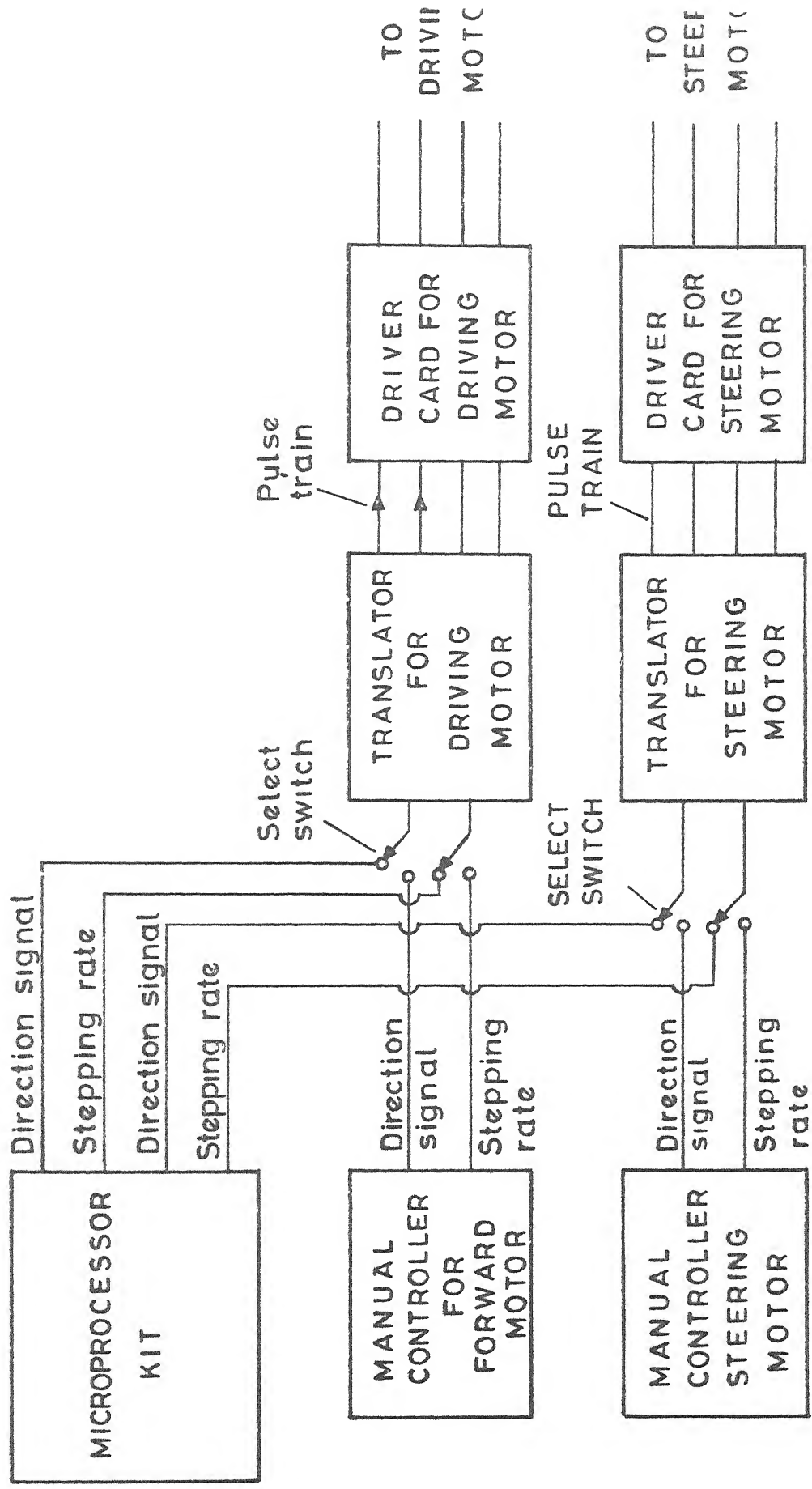


FIG. 3.3 BLOCK DIAGRAM OF CONTROL SCHEME

gives the oscillating signal (pulse) at the output. A potentiometer controls the frequency of this pulse and hence the speed of the motor. A D.P.D.T. switch along with a start latch and nand gate acts as ON-OFF switch for the motor motion by either allowing this pulse to go to the translator or by giving no pulse at the nand gate output. This pulse along with direction control bit now goes to the translator through the select switch. The translator converts this one pulse into four pulses of equal frequencies but with phase difference so that the correct sequence is maintained. It uses two exclusive or gates and two D flip-flops. Figure 3.4 is the circuit diagram of manual controller and translator. Two similar circuits are used to control motions of both the motors simultaneously. Using this controller the speed of the stepper motors can be varied from 3 RPM to 66 RPM.

### Microprocessor Based Controller

In programming mode the signals to the translators of both the driving and steering motors come from the microprocessor. When the motion required demands rotation of both the motors the microprocessor provides two clock pulses and two direction signals. Thus the microprocessor gives four bit output to the translators. An 8085 microprocessor kit is used for this purpose. The algorithm used to generate the signals is shown in the form of a flow chart in Figure 3.5.

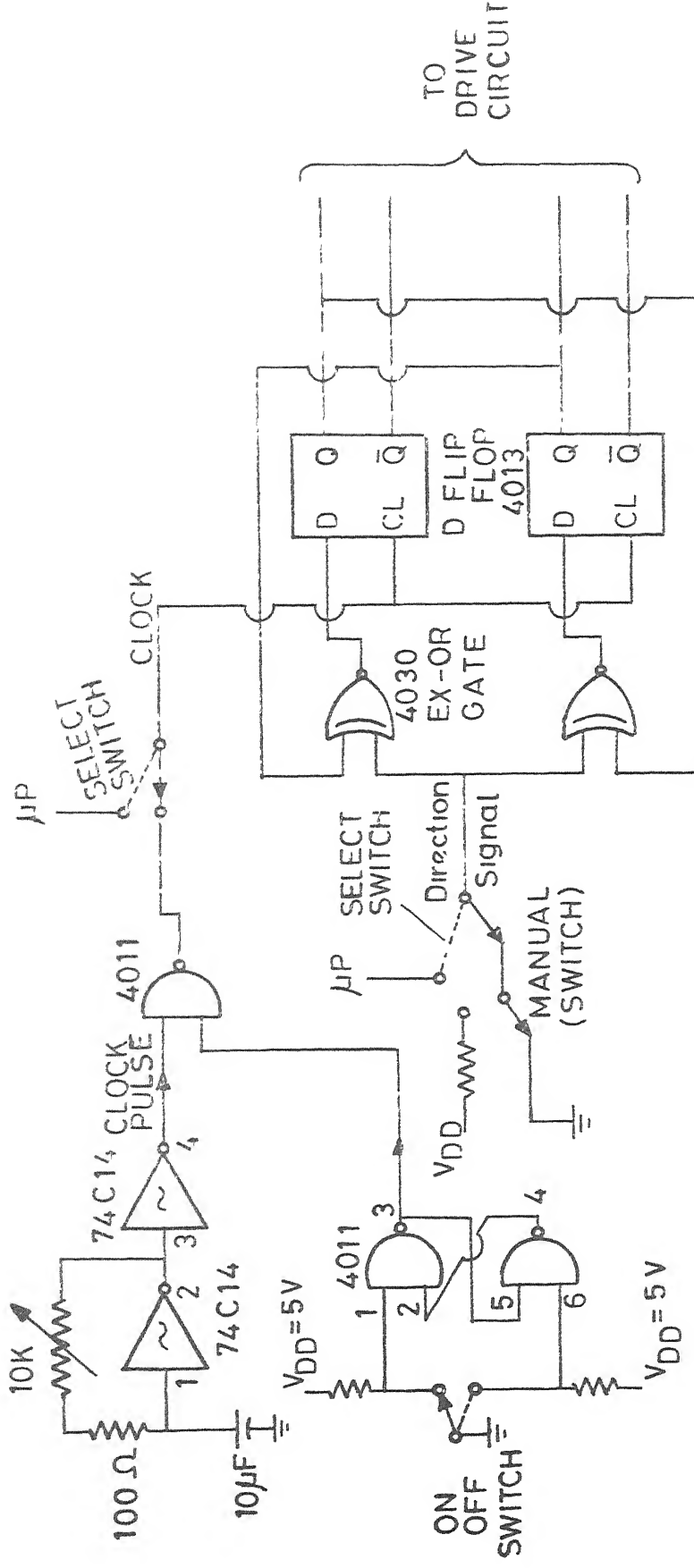


FIG. 3.4  
MANUAL CONTROLLER & TRANSLATOR

A display routine is written which displays on-off status of both the motors and twice the steps of forward motor remained to be completed. This display routine acts as a delay routine. This routine is called N times where N is the delay value loaded. After every N times the count values of both the motors are reduced by one and when any of the count value becomes zero the clock bit of that motor is changed and the step value is reduced by one. This procedure is repeated until the step value reduces to zero. Thus the microprocessor controls the motion of both the motors simultaneously. The listing of this routine is given in Appendix 2. along with the listing of the program for different paths [17,18] . Count value of the motors are stored in one byte memory for each motor, this limits the ratio of speed of two motors to 256. This ratio can be increased by keeping more bytes for the count value.

### 3.3 Design of Drive Circuit

The sequence of pulse train output of the translator are of low level signals and can not drive the motor and so a drive circuit is used to drive the motor. The function of the drive circuit is to accept low level input logic signals in the form of a digital pulse train from the translator and control the sequence of the high current to the motor phases in order to produce the discrete angular motion. To turn a motor phase ON, a voltage signal is applied to BC 147

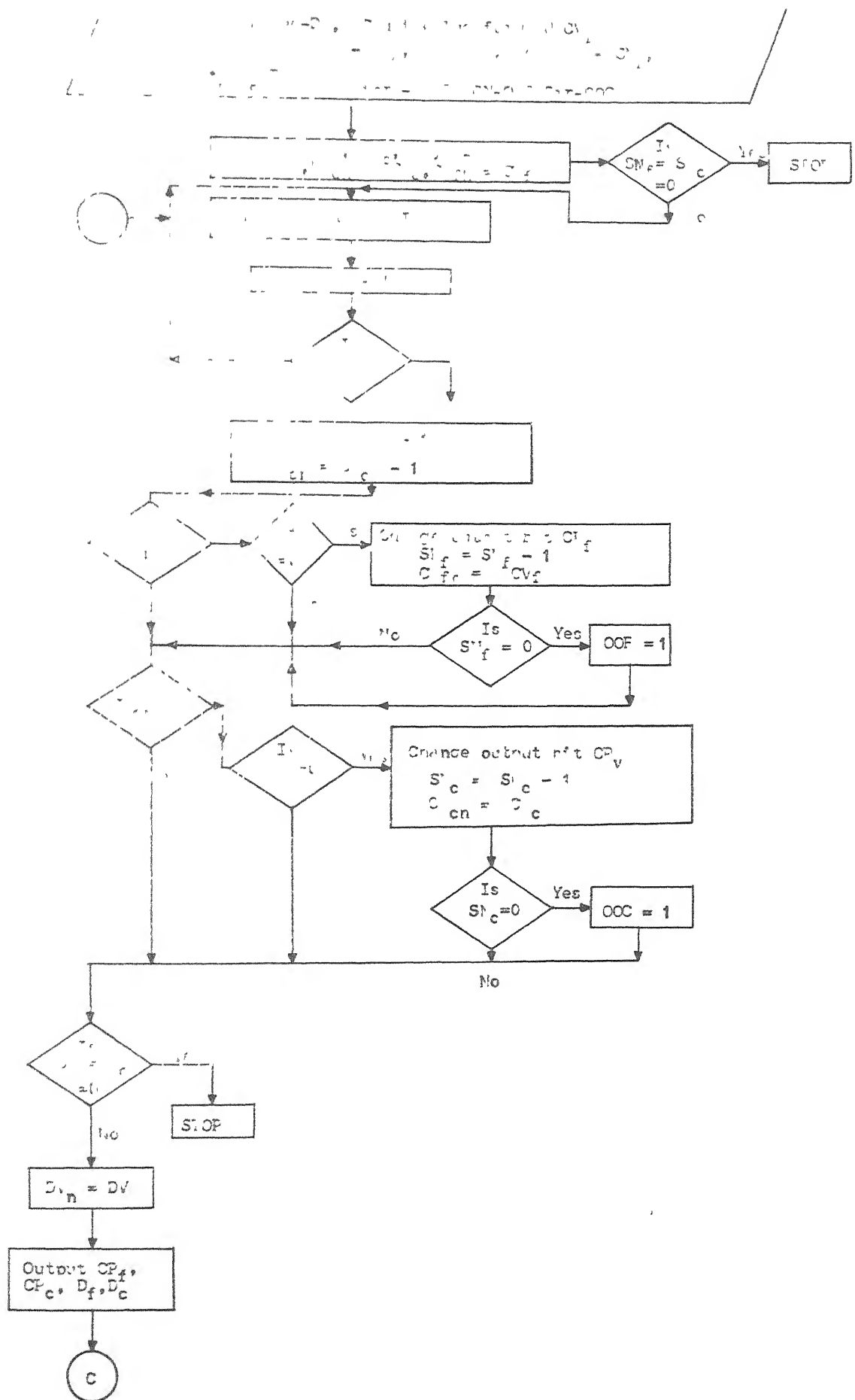


Figure 3.5 : Flow Chart for the Motion of the Vehicle



transistor to turn it ON. This, in sequence, turns ON  
OFF 1 transistor and 3055 power transistor which completes  
the circuit and the current builds up through the motor  
phase. When the motor phase is turned OFF by changing the  
signal at TC-147 transistor base, all three transistors  
are turned OFF. At this time the current in the motor phase  
decays through the flyback diode and thus discharges the  
motor phase. By repeating this process we can get discrete  
angular motion of the motor shaft. Figure 3.6 shows this  
circuit. Figure 3.7 shows layout of PCB for this circuit.

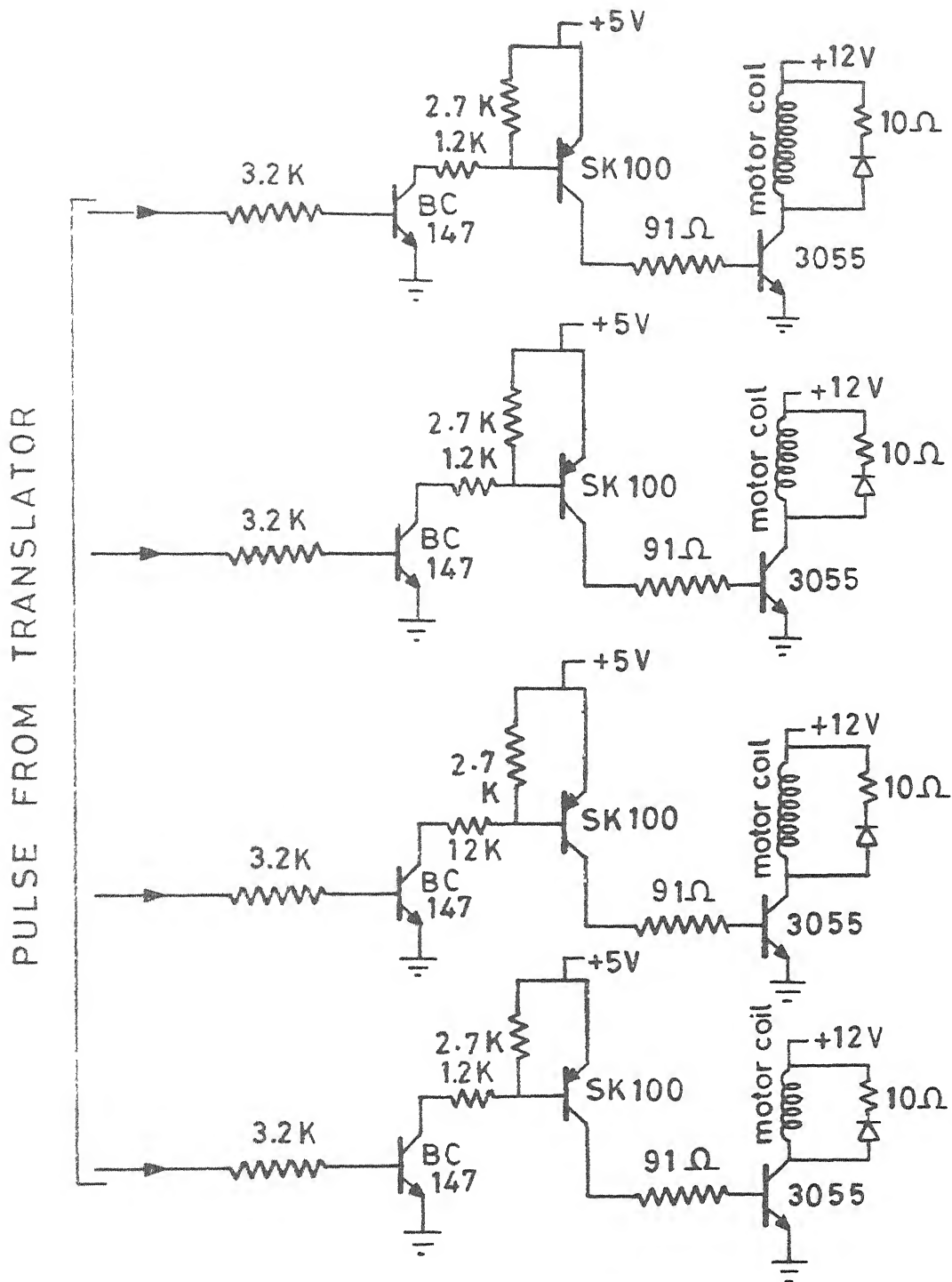


FIG. 3.6

DRIVE CIRCUIT FOR THE MOTOR

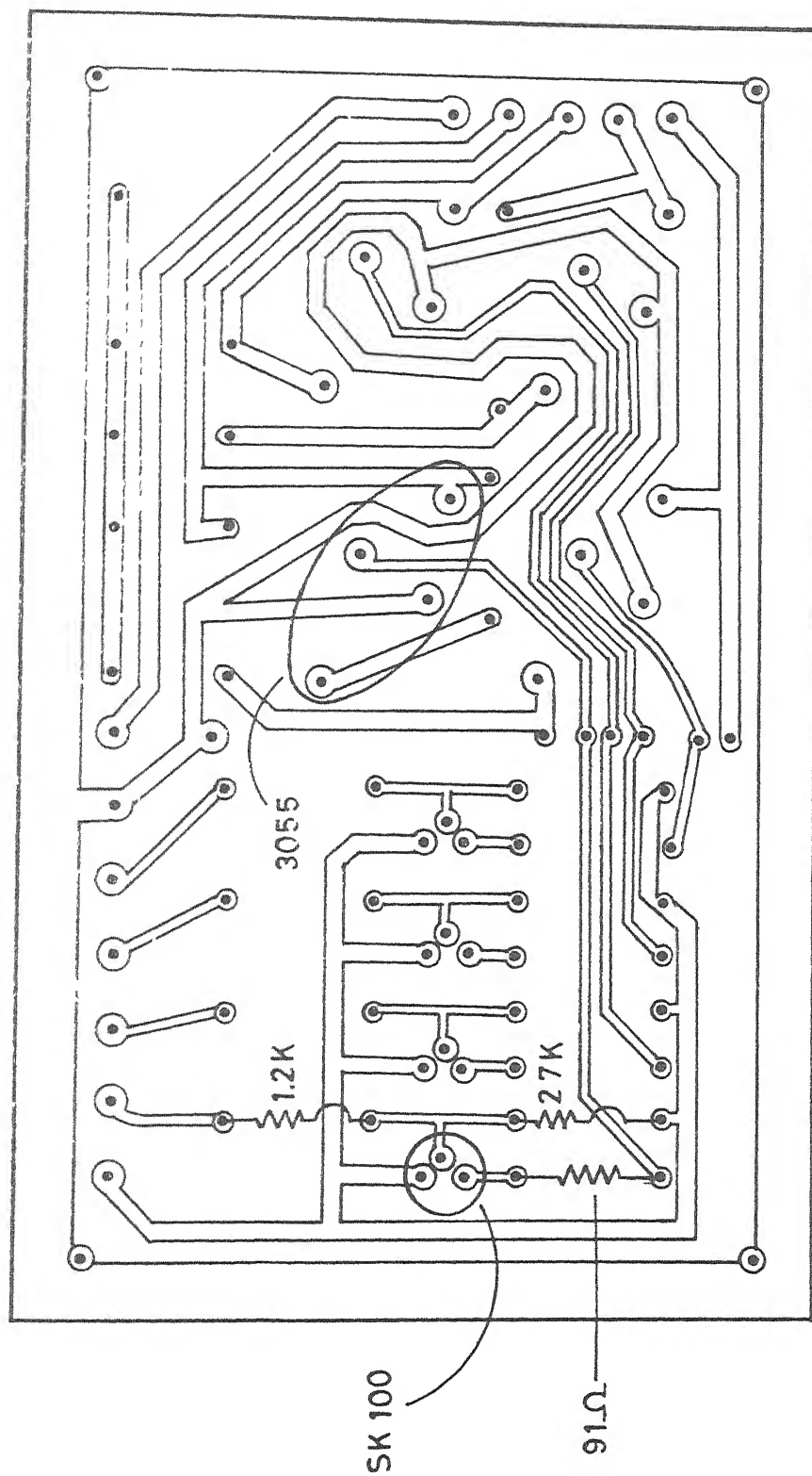


FIG. 3.7 PCB LAYOUT FOR DRIVE CIRCUIT

## CHAPTER 4

## RESULTS AND DISCUSSIONS

After completing the fabrication, the vehicle was tested in both the manual and the programmed mode.

In the manual mode operation, in order to reach the destination by avoiding the obstacles, the path taken was divided into a number of segments of straight lines and circular arcs. Thus both the path traced and the position of the vehicle were closely monitored and verified.

In the programmed mode, the microprocessor kit was programmed to take different paths. Program was written for taking three different paths, namely, a straight line, a circular path and a figure of 8 path. The program listing for the above shapes is given in the Appendix\_2. For moving along a figure of 8 path, the motion was carried out in eighteen steps. The vehicle motion was observed while tracing these paths.

While carrying out the experiments, it was found that the torque ratings of the motors specified by the maker are not correct. Torque of the motors fall rapidly with increasing the rotational speed. So all the experiments were carried out at low speed. In the manual mode, due to limitations put by the hardware, the speed ratio of the two motors was limited to 6.

It can be seen from that the vehicle deviates a little from the desired path during the operation. The driving shafts are not rotating with same angular velocity due to difference in the effective radii of the pulley and some slippage of the belts. There was some relative motion between the stepping shaft due to slight backlash in the gears. These factors caused deviation from the desired path. In the manual mode, the vehicle can reach a destination by controlling the path. However, since the operation was carried out in the open loop in the programmed mode, error could not be entirely eliminated.

This problem can be solved to a large extent by using a closed loop gear drive. In order to monitor the motion in programmed mode, feed back control scheme can be much more effective as the error can be compensated by the appropriate motion given by the software.

## REFERENCES

1. P. D. Allen, 'Hand Book of Industrial Robotics'.
2. P. D. Allen, 'Fundamentals of Robot Technology'.
3. Robert Jean, Coiffet Phillipp, 'Teleoperation and Robot Control: Evaluation and Development'.
4. P. D. Allen, 'Robots and Telechairs'.
5. P. D. Allen, John W., 'Rethinking Robot Mobility' Robotics Age, Jan 1985, pp. 26-30.
6. P. D. Allen, Thomas, 'Automated Guided Vehicles'.
7. P. D. Allen, Mark J., 'Advanced Robot Systems'.
8. P. D. Allen, 'Some Heuristics For the Navigation of a Robot', International Journal of Robotics Research, Spring 1983, pp. 59-66.
9. P. D. Allen, John W., 'Agile Autonomous Vehicles in the Just in Time Environment', Robotics Age, Dec. 1985, pp. 4-8.
10. P. D. Allen, 'Mechanical Engineers Handbook'.
11. National Engineering Industries Ltd. Jaipur 'CATALOGUE'.
12. P. D. Allen, 'Handbook of Gear Design'.
13. Kuo Benjamin, 'Theory and Application of Stepmotors'.
14. Billingsley John, 'DIY Robotics and Sensors with the BBC Computer'.
15. Patil, V.L., 'Interface Lets Microprocessor Control Stepper Motor'.
16. Semiconductors Limited 'CMOS Data Book'.
17. Leventhal Lance A, '8080A-8085 Assembly Language Programming'.
18. User's Manual for VMC-85 Microprocessor Kit.

## APPENDIX 1

### Calculations for Belt and Gear Drives

Calculations are presented here for belt and gear drives. Since load and torque acting is very less, emphasis is not given on strength aspect.

#### Belt Transmission:

From the motor to the driving shaft.

Diameter of pulleys  $D_1 = D_2 = 30\text{mm}$

$\theta_1 = \theta_2 = \pi$  radian.

Length of belt at outer surface,  $L = 45\text{ mm}$

Centre to centre distance between the pulleys

$$C = \frac{L - D}{2} = \frac{45 - 30}{2} = 17.78\text{ mm.}$$

#### Gear Transmission

(a) From the driving shaft to the wheel shaft

Pitch cone diameter  $d_1 = 46\text{ mm}$

Module  $m = 2\text{ mm}$

Number of teeth  $= 23$

Pitch cone angle  $= 45^\circ$

Face width  $= 8\text{ mm}$

Tip circle diameter  $= d + 2m \cos$

$$= 46 + 2 \times 2 \times \cos 45$$

$$= 48.3\text{ mm.}$$

$$\begin{aligned}\text{Cone distance } R_1 &= \frac{d}{2\sin} \\ &= 32.52\end{aligned}$$

$$\begin{aligned}\text{Addendum Angle} &= \tan^{-1} \frac{m}{R} \\ &= 3.5185^\circ\end{aligned}$$

$$\begin{aligned}\text{Dedendum Angle} &= \tan^{-1} \frac{1.2m}{R} \\ &= 4.22^\circ\end{aligned}$$

$$\begin{aligned}\text{Blank cone Angle} &= \text{Cone angle} + \text{Addendum Angle} \\ &= 48.5^\circ\end{aligned}$$

$$\begin{aligned}\text{Root Angle} &= \text{Cone Angle} - \text{Dedendum Angle} \\ &= 40.78^\circ\end{aligned}$$

(b) Between the steering motor and the steering shaft.

In order to keep velocity ratio unity, the gears on the motor and the steering shaft are identical. Gears placed at the end of the connecting shaft are also made identical.

Calculation for one such pair is shown here.

$$\text{Pitch cone diameter of gear } d_1 = 57.5 \text{ mm}$$

$$\text{Pitch cone diameter of pinion } d_2 = 27.5 \text{ mm}$$

$$\text{Module } m = 1.25 \text{ mm}$$

$$\text{Face width} = 8 \text{ mm}$$

$$\text{Number of teeth on gear } T_1 = 46$$

$$\text{Number of teeth on pinion } T_2 = 22$$

$$\begin{aligned}\text{Pitch cone angle of pinion } \delta_2 &= \tan^{-1} \frac{27.5}{57.5} \\ &= 25.6^\circ\end{aligned}$$



$$\begin{aligned}\text{Pitch cone angle of the gear } \delta_1 &= 90 - \delta_2 \\ &= 64.4^\circ\end{aligned}$$

$$\begin{aligned}\text{Tip circle diameter of the gear} &= d_1 + 2m \cos \delta_1 \\ &= 57.5 + 2 \times 1.25 \times \cos 64.4^\circ \\ &= 58.58 \text{ mm}\end{aligned}$$

$$\text{Cone distance } R_1 = \frac{d_1}{2 \sin \delta_1} = 31.87 \text{ mm}$$

$$\begin{aligned}\text{Addendum Angle} &= \tan^{-1} \frac{m}{R} \\ &= 2.246\end{aligned}$$

$$\begin{aligned}\text{Dedendum Angle} &= \tan^{-1} \frac{1.2m}{R} \\ &= 2.695\end{aligned}$$

$$\begin{aligned}\text{Blank cone angle for the gear} &= 64.4 + 2.246 \\ &= 64.65^\circ\end{aligned}$$

$$\begin{aligned}\text{Root angle for the gear} &= 64.4 - 2.7 \\ &= 61.7^\circ\end{aligned}$$

$$\begin{aligned}\text{Blank cone angle for the pinion} &= 25.6 + 2.246 \\ &= 27.85^\circ\end{aligned}$$

$$\begin{aligned}\text{Root angle for the pinion} &= 25.6 - 2.695 \\ &= 22.9^\circ\end{aligned}$$

## APPENDIX 2

### LISTING OF PROGRAMME

ADDRESS	CODE	MNEMONIC	REMARKS
FE90	3E/80	RUN8 MVI A,80	Initialise 8255 in
FE92	D3 03	OUT 03	mode 0 with B as
FE94	2A 02 FF	LHLD FF02	output port
FE97	22 0A FF	SHLD FFDA	COPY COUNT VALUES
FE9A	AF	XRA A	--
FE9b	D3 19	OUT 19	Initialising 8279
FE9d	21 04 FF	LXI H,FF04	Steps for F/W motor
FEA0	5E	MOV E,M	in D-E pair
FEA1	23	INX H	
FEA2	56	MOVE D,M	
FEA3	23	INX H	Steps for CR motor
FEA4	4E	MOVE C,M	in B-C Pair
FEA5	23	INX H	
FEA6	46	MOVE B,M	
FEA7	13	INX D	
FEA8	03	INX B	
FEA9	C3 00 FE	JMP START	JUMP TO MAIN
			ROUTINE
MAIN ROUTINE			
FE00	CD 00 FC	START:CALL DELAY	
FE03	21 09 FF	LXI H,FF09	
FE06	7E	MOV A,M	Get ON OFF Status

FE 07	E6	03		ANI	03	
FE 08	FE	03		CPI	03	If both motors to be off then return
FE 0F	23			INX	H	If count of F/W exhausted then call service routine
FE 0F	35			DCR	M	
FE 10	CC	30	FE	CZ	F/W SRVC	
FE 13	23			INX	H	If count of CR exhausted then call service routine
FE 14	35			DCR	M	
FE 15	CC	60	FE	CZ	RIV SRVC	
FE 18	C3	00	FE	JMP	START	
FE 20	C9			STOP :	RET	Return to main program

#### SERVICE ROUTINE FOR FORWARD MOTOR

FE 30	1F			F/W SRVC:RAR		Check if ON OFF FLAG BIT IS 1
FE 31	DA	48	FE	JC	F/W OFF	
FE 34	3A	02	FF	LDA	FF02	
FE 37	77			MOV	M,A	
FE 38	1B			DCX	D	
FE 39	7A			MOV	A,D	Check if number of steps for F/W motor exhausted
FE 3A	B3			ORA	E	
FE 3B	CA	50	FE	JZ	F/E FINISH	JUMP F/W FINISH
FE 3E	3A	08	FF	LDA	FF08	Flip the bit for F/W Clock and output the result
FE 41	EE	80		XRI	80	
FE 43	32	08	FF	STA	FF08	
FE 46	D3	01		OUT	01	
FE 48	C9			F/W OFF:RET		

# R/W FINISH:

FE 50	3A 09 FF	LDA, FF09	Change ON-OFF flag bit
FE 53	F6 01	ORI 01	
FE 55	32 09 FF	STA FF 09	
FE 58	C9	RET.	

## SERVICE ROUTINE FOR STEERING MOTOR

FE 60	3A 09 FF	LDA FF09	Check ON-OFF flag bit
FE 63	1F	RAR	
FE 64	1F	RAR	
FE 65	DA 7C FE	JC:CR OFF	
FE 68	3A 03 FF	LDA FF03	Reload count
FE 6B	77	MOV M,A	
FE 6C	0B	DCX B	-
FE 6D	78	MOV A,B	Check if number of steps for cir mor exhausted
FE 6E	B1	ORA C	
FE 6F	CA 80 FE	JZ: CR FINISH	JUMP CR FINISH
FE 72	3A 08 FF	LDA FF08	FLIP the bit for CR clock and out- put the result
FE 75	EE 02	XRI 02	
FE 77	32 08 FF	STA FF03	
FE 7A	D3 01	OUT 01	
FE 7C	C9	CR OFF:RET	

## CR FINISH :

FE 80	E5	PUSH H	Change ON-OFF Flag bit
FE 81	3A 09 FF	LDA FF09	
FE 84	21 0D FF	LX1 H , FF0D	
FE 87	B6	ORA M	

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FE 88	32 09 FF	STA FF09
FF 8B	E1	POP H
FF 8C	C9	RET

# DISPLAY ROUTINE

FC 00	C5	PUSH BC	
FC 01	2A 00 FF	LHLD FFOO	
FC 04	44	MOV B,H	
FC 05	4D	MOV C,L	
FC 06	26 FC	MVI H, FC	
FC 08	3E 90	RPT: MVI A,90	
FC 0A	D3 19	OUT 19	Initialise 8279
FC 0C	7A	MOV A,D	
FC 0D	E6, FO	ANI FO	
FC 0F	1F	RAR	
FC 10	1F	RAR	Display first bit of steps
FC 11	1F	RAR	
FC 12	1F	RAR	
FC 13	2E 60	MVI L,60	
FC 15	85	ADD L	
FC 16	6F	MOV L,A	
FC 17	7E	MOV A,M	
FC 18	D3 18	OUT 18	
FC 1A	7A	MOV A,D	Display second bit of steps
FC 1B	E6 OF	ANI OF	
FC 1D	2E 60	MVI L 60	
FC 1F	85	ADD L	

FC 20	6F		MOV L,A	
FC 21	7E		MOV A,M	
FC 22	D3	18	OUT 18	
FC 24	7B		MOV A,E	DISPLAY Third bit
FC 25	E6	FO	ANI FO	
FC 27	1F		RAR	
FC 28	1F		RAR	
FC 29	1F		RAR	
FC 2A	1F		RAR	
FC 2B	2E	60	MVI L,60	
FC 2D	85		ADD L	
FC 2E	6F		MOV L,A	
FC 2F	7E		MOV A,M	
FC 30	D3	18	OUT 18	
FC 32	7B		MOV A,E	Display forth bit
FC 33	E6	OF	ANI OF	
FC 35	2E	60	MVI L,60	
FC 37	85		ADD L	
FC 38	6F		MOV L,A	
FC 39	7E		MOV A,M	
FC 3A	D3	18	OUT 18	
FC 3C	3A	09 FF	LDA FF09	
FC 3F	6F		MOV L,A	
FC 40	1F		RAR	
FC 41	1F		RAR	
FC 42	3E	03	MVI A,03	Display for direction
FC 44	D2	49 FC	JNC zero	

FC 47	3E 4F		MV1 A,9F	
FC 49	D0 18		Zero: OUT 18	
FC 4B	7D		MOV A,L	
FC 4C	1F		RAR	
FC 4D	3E 03		MV1 A,03	Display for direction
FC 4F	D2 54 FC		JNL ZR	
FC 52	3E 9F		MV1 A,9F	
FC 54	D3 18		ZR: OUT 18	
FC 56	0B		DCX B	
FC 57	78		MOV A,B	
FC 58	D1		ORA C	
FC 59	C2 08 FC		JNZ RPT	
FC 5C	C1		POP BC	
FC 5D	C9		RET	

#### TABLE FOR DISPLAY

		Display code for
FC 60	03	0
FC 61	9F	1
FC 62	25	2
FC 63	0D	3
FC 64	99	4
FC 65	49	5
FC 66	41	6
FC 67	1F	7
FC 68	01	8

FC 69	09	9
FC 6A	11	A
FC 6B	C1	B
FC 6C	63	C
FC 6D	85	D
FC 6E	61	E
FC 6F	71	F

# PROGRAM

FD 00	31	60	FF	PROG: LXI SP FF60	
FD 03	21	70	00	LXI H 0070	LOAD DELAY
FD 06	22	00	FF	SHLD FF00	
FD 09	CD	70	FC	CALL STR	CALL STR
FD 0C	CD	8A	FC	CALL CRC	CAL CRC
FD 0F	21	02	08	LXI H 0802	LOAD COUNT
- 12	21	02	FF	SHLD FF02	VALUE
FD 15	21	90	01	LXI H 01 90	LOAD STEPS F/W
FD 18	22	04	FF	SHLD FF04	
FD 1E	21	64	00	LXI H 0064	LOAD STEPS CR
FD 1E	22	06	FF	SHLD FF06	
FD 21	CD	61	FD	CALL R1	
FD 24	00	00		NO OP	
FD 26	21	00	02	LXI H 0200	LOAD OUTPUT
FD 29	22	08	FF	SHLD FF 08	CONTROL
FD 2C	CD	90	FE	CALL RUN	



FD 2F	21 00 01	LX1 01 00	LOAD OUTPUT CONTROL
FD 32	22 08 FF	SHLDF F 08	
FD 3E	CD 90 FD	CALL R3	LOAD COUNT VALUE
FD 38	3E 08	MV1 A,08	
FD 3A	32 03 FF	STA FF 03	
FD 3D	CD 90 FD	CALL R4	
FD 40	CD 90 FD	CALL R4	LOAD OUTPUT CONTROL
FD 43	CD 90 FD	CALL R4	
FD 46	CD 90 FD	CALL R4	
FD 49	21 FF 01	LX1 H 01 FF	
FD 4C	22 08 FF	SHLD FF 08	LOAD COUNT VALUE
FD 4F	CD 80 FD	CALL R3	
FD 52	3E 08	MV1 A 08	
FD 54	32 03 FF	STA FF 03	
FD 57	CD 70 FD	CALL R2	LOAD OUTPUT CONTROL
FD 5A	CD 61 FD	CALL R1	
FD 5D	CD 61 FD	CALL R1	

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# ROUTINE

FD 61	21 64 00	LX1 H 0064	LOAD STEPS CR
FD 64	22 06 FF	SHLD FF06	
FD 67	21 00 02	LX1 H 0200	LOAD OUTPUT CONTROL
FD 6A	22 08 FF	SHLD FF08	
FD 6D	CD 90 EE	CALL: RUN	
FD 70	21 64 00	LX1 H 0064	
FD 73	22 06 FF	SHLD FF 06	

FD 76	21	00	00	LX1	00	00
FD 79	22	08	FF	SHLD	FF	08
FD 7C	CD	90	FE	CALL	RUN	
FD 7F		C9		RET		
FD 80	21	C8	00	LX1	H,00C8	
FD 83	22	06	FF	SHLD	FF	06
FD 86	3E	01		MV1	A	01
FD 88	32	03	FF	STA	FF	03
FD 8B	CD	90	FE	CALL	RUN	
FD 8E		C9		RET		
FD 90	21	64	00	LX1	H, 00 64	
FD 93	22	06	FF	SHLD	FF06	
FD 96	21	FF	00	LX1	H, 00 FF	
FD 99	22	08	FF	SHLD	FF	08
FD 9C	CD	90	FE	CALL	RUN	
FD 9F	21	FF	02	LX1	H, 02 FF	
FD A2	22	08	FF	SHLD	FF	08
FD A5	CD	90	FE	CALL	RUN	
FD A8		C9		RET		
FC 70	21	02	08	LX1	H,08 02	
FC 73	22	02	FF	SHLD	FF	02
FC 76	21	B0	04	LX1	H, 04 B0	
FC 79	22	04	FF	SHLD	FF	04
FC 7C	21	C8	00	LX1	H,00 C8	
FC 7F	22	06	FF	SHLD	FF	06
FC 82	21	FF	02	LX1	H, 02 FF	

FC 83	22	08	FF	SHLD FF 08
FC 86	CD	90	FE	CALL RUN
FC 89		C9		RET
FC 8A	21	02	10	LXI H, 1002
FC 8D	22	02	FF	SHLD FF 02
FC 90	21	50	04	LXI H, 04 B0
FC 93	22	04	FF	SHLD FF 04
FC 96	21	00	01	LXI H, 01 00
FC 99	22	66	FF	SHLD FF 06
FC 9C	21	FF	00	LXI H, 00 FF
FC 9F	22	08	FF	SHLD FF 08
FC A3	CD	90	FE	CALL RUN
FC A6		C9		RET.

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